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FLOW FRICTION OF THE TURBULENT COOLANT FLOW IN CRYOGENIC POROUS CABLES

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THERMAL ANALYSIS OF TURBULENT FLOW OF A SUPERCRITICAL FLUID

by

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THERMAL ANALYSIS OF TURBULENT FLOW OF A SUPERCRITICAL FLUID

by

Eitaro Yamane

1. Introduction

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In studying the transmission of heat in fluids subject to supercritical pressure, we observe, for relatively low thermal flow values, a major increase in the heat transmission coefficient when the average temperature of the fluid mixture in turbulent flow within a tube approaches its pseudocritical temperature.

There are differences of opinion in the attempt to explain the mechanism which occurs in this process of heat transmission. Some researchers, such as Knapp and Sabersky [1], Yamagata et. al. [2], Goldmann [3] and Shitsman [4], assume that to explain this singular behavior of the heat transmission coefficient in the neighborhood of the pseudocritical temperature one must resort to the existence of a phenomenon similar to that of nucleated or pelicular boiling in subcritical fluids. This leads to the theory of pseudoboiling in supercritical fluids for whose explanation it would perhaps be necessary to postulate the transient coexistence of two phases at supercritical pressures.

Other researchers, such as Bourke et al. [5], Tanaka et al. [6] and Swenson, Carver and Kakarala [7], assume that this singularity in the neighborhood of the pseudocritical temperature can be explained as being caused merely by a major variation of the thermodynamic and transfer properties at pseudocritical temperature.

Although it may be difficult to select one or another theory, taking into account the experimental observations of the phenomenon, this author agrees with the researchers who defend the

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* Numbers in the margin indicate pagination in the foreign text.

second theory, i.e., he is of the opinion that the major variation of the thermodynamic and transfer properties at pseudocritical temperature, conveniently taken into account in the function performed by the spins can then explain the singularity of the membrane's coefficient in its neighborhood.

Various studies, both experimentaland theoretical, have already been published on this subject. For the case of forced turbulent flow of a supercritical fluid within a tube, the theoretical analyses by Deissler [8], Wilderecht and Sonnemann, extended to the case of supercritical fluid by Hess and Kunz [9], Goldmann [3], Tanaka et al. [6] and Shiralkar and Griffith [10] are well known. These analyses take into account the shear stress and the thermal flow, both invariable, and with a linear variation in the radial direction, which would be subject to discussion for the case of supercritical fluid which represents a high degree of property variation in the radial direction in nonisothermal flow. All the theoretical analyses mentioned also assume the equality of the thermal spin diffusibilities and of the momentum, $\varepsilon_M = \varepsilon_T$ /425 and differ essentially from one another only in the ratios employed to determine the value of the spin diffusibility of the momentum.

In the theoretical analysis of this study the supercritical fluid flow is being considered within a smooth cylindrical tube in a turbulent regime with the profile of velocity fully developed. For the sake of simple presentation, the cases of constant and axisymmetrical thermal flow are being considered.

In order to approach real conditions as much as possible, the following is being considered in this study:

a - a real variation of a thermal flow in the radial direction obtained by the application of the first principle of thermodynamics;

b - a linear variation, in the radial direction, of the shear stress;

c - a ratio between the thermal spin diffusibilities and the momentum different from unity (the turbulent Prandtl number dif-

fers from unity, a function of the point considered, for each set of values of the parameters which influence this process.

2. Basic Equations

The equations of momentum and energy, in the forms indicated below, are the fundamental equations which, integrated for each section of the tube, will yield the distributions of velocity and temperature:

$$\tau = \rho \left(\nu + \varepsilon_M \right) \frac{du}{dy} \tag{1}$$

$$\frac{q}{\rho c_p} = -\left(\alpha + \varepsilon_T \right) \frac{dT}{dy} \tag{2}$$

where τ = shear stress; ρ = density; ν = kinetic viscosity; ε_M = spin diffusibility of the momentum; α = thermal diffusibility; ε_T = spin thermal diffusibility; μ = velocity component in the principal flow direction (x); T = temperature; y = coordinate perpendicular to the tube surface, with the origin at this surface. /426

To permit considering the variation of properties that occcur in the supercritical fluids in the universal distribution of velocity, $u^+ = f(y^+)$, the nondimensional velocities and distances are defined according to Goldmann [3], by:

$$u^+ = \int_0^u \frac{du}{u^*} \quad e \tag{3}$$

and

$$y^+ = \int_0^y \frac{u^*}{\nu} dy \tag{4}$$

where u^* is the shear or attrition velocity, defined by

$$u^* = \sqrt{\frac{\tau_o}{\rho}} \tag{5}$$

If we introduce these expressions in the equation of momentum, we obtain

$$\frac{\tau}{\tau_o} = \left(1 + \frac{\varepsilon_M}{\nu}\right) \frac{du^+}{dy^+} \qquad (6)$$

which formally is the same as that obtained in the case in which the properties are considered constant. Thus, the same formal expression of the spin diffusivity of the momentum obtained for the case of fluid flow with constant properties can be employed, provided expressions (3) and (4) are being used.

The spin diffusivity of the momentum used is that developed by Spalding [11]:

$$\frac{\varepsilon_M}{\nu} = \frac{\tau}{\tau_o}\left(1,0 + 0,04432\left[\exp(0,4u^+) - 1,0 - 0,4\,u^+ - \frac{(0,4u^+)^2}{2!} - \frac{(0,4u^+)^3}{3!}\right]\right) - 1,0 \qquad (7)$$

The thermal spin diffusivity used is that obtained by Yamane [12] by means of a modification in the theory of the Prandtl mixture length and is based on the calculation of transfer efficiency of momentum and energy: /427

$$\frac{\varepsilon_T}{\varepsilon_M} = \frac{1,0+\exp\left(-\dfrac{6\,\eta_M}{N_{Pr}\left(\frac{\varepsilon_M}{\nu}\right)}\left[2,0+0,6N_{Pr}^{\frac{1}{3}}\left(\frac{\varepsilon_M}{\nu}\frac{1}{\eta_M}\right)^{\frac{1}{2}}\right]\right)}{\left[\left(0,40972\,\frac{\varepsilon_M}{\nu}\right)^2 + 0,888\,\frac{\varepsilon_M}{\nu}\right]^{\frac{1}{2}} - 0,40972\,\frac{\varepsilon_M}{\nu}} \qquad (8)$$

where

$$\eta_M = 0,5\left\{\left[\left(0,40972\,\frac{\varepsilon_M}{\nu}\right)^2 + 0,8888\,\frac{\varepsilon_M}{\nu}\right]^{\frac{1}{2}} - 0,40972\,\frac{\varepsilon_M}{\nu}\right\}$$

3. Results

Considering a linear distribution of the shear stress and a thermal flow distribution given by the first principle of

thermodynamics, the fundamental equations and the differential equations which define the characteristic parameters are integrated by the numerical method of Runge-Kutta-Gill and furnish the velocity distribution, the temperature distribution, the average temperature of the mixture (based on the average enthalpy of the mixture), and the membrane coefficient for given values of thermal flow on the surface (q_o) and of the discharge ($\dot{m}$).

The Runge-Kutta-Gill method is applied in this case by means of an iteration process with respect to the shear stress on the surface whose value is a discharge function; and due to the variation of the thermodynamic and transfer properties as a function of temperature, the equations are simultaneously integrated.

In this manner, for the case of carbon dioxide whose properties are reasonably well known, we can obtain graphs such as those furnished by the velocity distribution, the temperature distribution and the membrane coefficient for given values of the characteristic parameters.

Fig. 1 represents the comparative graphs of the results obtained from this theoretical analysis with the experimental results and of the theoretical analysis performed by Tanaka et al. [6] and shows good agreement with the experimental results. Particularly Fig. 2, which locates the elements of the fluid at a pseudocritical temperature is the one which is of interest to the thermal analysis of this study. /428

4. Thermal Analysis

From the equation of energy (2), we obtain

$$\Delta T_{total} = T_o - T_c = \int_o^{y_c} - \frac{q}{k+\rho\, c_p \varepsilon_T}\, dy = (\Delta T)_{SCL} + (\Delta T)_{CA} + (\Delta T)_{CT} \qquad (9)$$

where y_c = the value of y at the center of the tube; SCL refers /429 to the laminar sublayer (y^+ between 0 and 5); CA refers to the

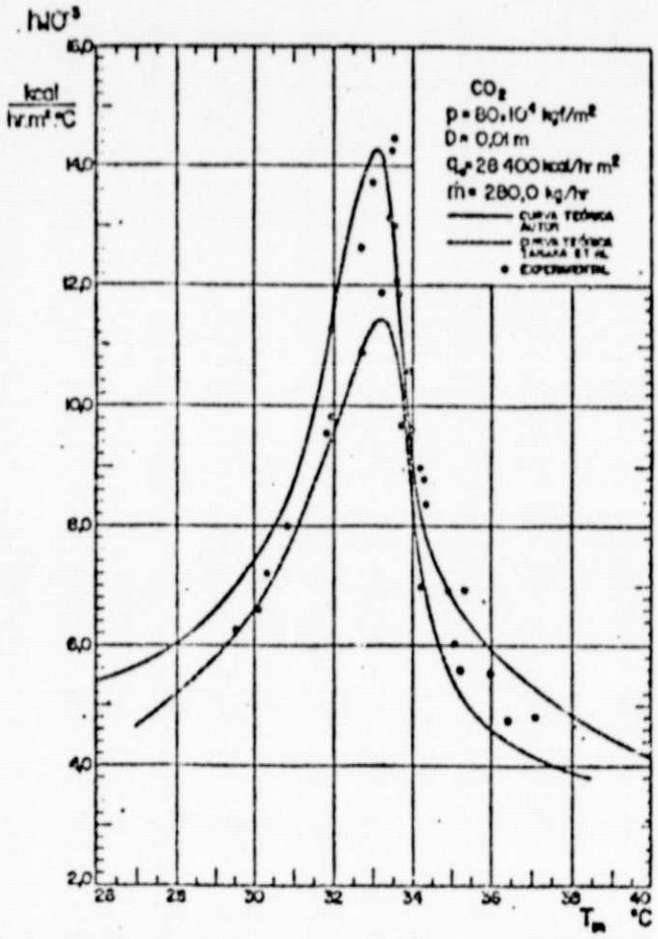

Fig. 1. Comparison between the theoretical curves of the heat transfer coefficient and the experimental points.

——— theoretical curve by author.
----- theoretical curve obtained by Tanaka et al.
..... experimentation

buffer layer (y^+ between 5 and 30); CT refers to the turbulent layer ($y^+ > 30$) and $\underline{k}$ = thermomolecular conductivity.

The heat transfer coefficient in the case of turbulent flow may be calculated approximately as follows:

$$h = \frac{q_o}{T_o - T_m} \cong \frac{q_o}{T_o - T_c} \qquad (10)$$

where T_o = temperature of the internal tube surface; T_m = average temperature of the mixture; T_c = temperature at the center of the tube and h = coefficient of heat transfer.

Therefore, the membrane coefficient will have a high value when $(\Delta T)_{total}$ is small, i.e. when $(k + \rho c_p \varepsilon_T)$ is large. This will happen when the temperature at certain points in the fluid is in the zone of the pseudocritical temperature, because at that temperature $\underline{k}$ and ρc_p will have maximal values.

However, so that the effect of this major increase in values of the properties at pseudocritical temperature may become noticeable, causing a reduction in the thermal resistance, it is necessary for the fluid element which is at the pseudocritical temperature to be located within the buffer zone, i.e. in the interval of the nondimensional distance, y^+, between 5.0 and 30.0.

If the fluid point where the temperature is pseudocritical is located in the turbulent layer, the effect of the increase of those properties, $\underline{K}$ and pc_p, will be small because in this layer, the thermal resistance is already much smaller with respect to the other layers due to the high value of the spin thermal diffusivity ε_T. Therefore, in this case, the increase in the membrane coefficient due to the increase in the property values will not be significant. /430

If the point whose temperature is pseudocritical is located

in the laminar sublayer, the contribution to the increase in the membrane coefficient will be only $\underline{k}$ because ($\rho\ c_p\ \varepsilon_T$) in this layer is negligible due to the value of the diffusivity ε_T. And since the increase of $\underline{k}$ is relatively small compared to the specific heat, the effect of the variation of properties upon the increase of the membrane coefficient will also not be significant.

If on the other hand, the fluid element at pseudocritical temperature is located in the buffer zone where the terms $\underline{k}$ and $\rho\ c_p\ \varepsilon_T$ are of the same order of magnitude and where $(\Delta T)_{CA}$ constitutes the major portion of $(\Delta T)_{total}$, the simultaneous increase of $\underline{k}$ and $\rho\ c_p$ at the pseudocritical will yield a considerable decrease in $(\Delta T)_{total}$. In this manner, greater values of the membrane coefficient will be obtained resulting in the formation of those characteristic peaks of the coefficient, shown in Figs. 1 and 2.

Fig. 2 confirms the analysis performed above. We show the curve of the points y^+ for which the temperature is the pseudocritical temperature as a function of the average temperature of the mixture for the conditions indicated in the figure. It can be verified that the peak of the membrane coefficient occurs when the point of the fluid which is at the pseudocritical temperature is located in the interval $5 < y^+ < 30$ corresponding to the buffer layer.

5. Conclusions /431

The theoretical analysis of the process of heat transfer of a supercritical fluid, flowing in a turbulent regime within a tube, performed in this study, leads to results which present good agreement with the experimental results in the region of the peak characteristic of the membrane coefficient. This analysis permits an explanation of the formation of the characteristic peak and justifies the necessity of the fluid element at pseudocritical temperature to be located in the buffer layer for a major increase

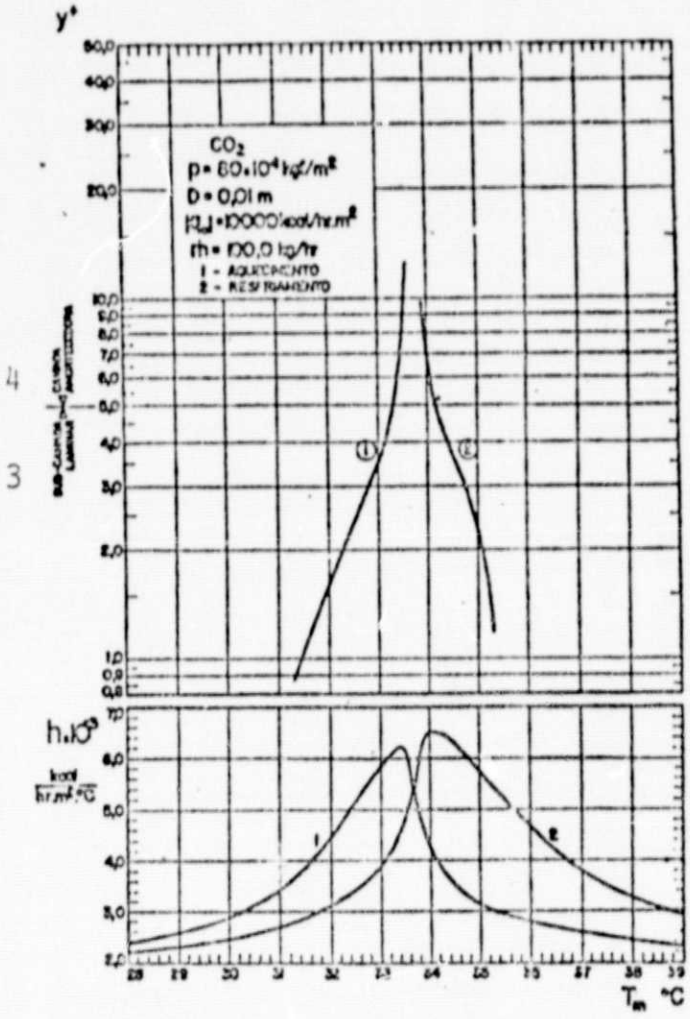

Fig. 2. Location of the fluid elements at pseudocritical temperature.

Key: 1. heating
2. cooling
3. laminar sublayer
4. buffer layer

in the heat transfer coefficient to occur. By similar reasoning to that of the previous section, the thermal analysis of the mechanism of the heat transfer process also permits us to explain the following:

a - the formation of the peak of the heat transfer coefficient at an average mixture less than in the case of heating;

b - a reduction in the value of the peak of the heat transfer coefficient as a function of the increase in the absolute value of the thermal flow when the discharge is maintained constant;

c - obtaining a higher value for the peak of the coefficient in case of cooling than that for heating, maintaining the absolute value of the thermal flow and the discharge constant.

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